N94-33307

HIGH PRECISION MOVING MAGNET CHOPPER FOR VARIABLE OPERATION CONDITIONS

Winfried Aicher and Manfred Schmid
Dornier GmbH
Friedrichshafen, Germany

Abstract

In the frame work of an ESTEC technology contract a Chopping Mechanism was developed and built with FIRST (Far Infrared and Submillimeter Telescope) astronomy mission as a reference. The task of the mechanism is to tilt the subreflector of the telescope with an assumed mass of 2.5 kg about one chopping axis at nominal frequencies of up to 5 Hz and chopping angles of up to +/- 11.25 mrad with high efficiency (minimum time for position change). The chopping axis is required to run through the subreflector vertex.

After performing a concept trade-off also considering the low operational temperatures in the 130 K range, a design using moving magnet actuators was found to be the favorite one. In addition, a bearing concept using flexible pivots was chosen to meet the high chopping accuracy required.

With this general concept approach a very reliable design could be realized since the actuators work without any mechanical contact between its moving and fixed parts and the only bearings used are two flexible pivots supporting the subreflector mounting interface.

The mechanism was completely built in titanium in a lightweight and stiff design, the moving magnet actuators were designed to meet the stringent requirements for minimum risetime (time necessary to move from one angular position to a new one) in the 20 msec range. The angular position and the corresponding chopping frequency as well can be arbitrarily selected by the user.

The mechanism is equipped with two linear sensors of high resolution. One of them is used to control the exact working position, the second one is used for position readout. The linearity of the sensors were calibrated under low temperature environment so that it is possible to compensate for the temperature drift.

After complete integration, the mechanism was functionally tested under ambient and thermal-vacuum conditions as well. It was found that the mechanism works perfectly under all temperature conditions and the most of the performance requirements were achieved.

Only the risetime which was specified to be within 20 msec for an angle of 3,75 mrad, was exeeded by about 30%.
The reason for this behaviour was found in a lower actuator force than expected, caused by magnetic effects and cross flux influences in the actuator.

Fig. 1 depicts an overview of the mechanism hardware.

Fig. 1: Chopping Mechanism Hardware

Introduction

Based on an ESTEC technology study a Focus and Chopping Mechanism (FCM) was developed on the example of the FIRST telescope requirements. The FCM can physically be subdivided in two mechanisms, namely the Focusing Mechanism and the Chopping Mechanism.

The function of the Focusing Mechanism is to axially refocus the subreflector of the telescope at a stroke of up to 5 mm with a resolution in the 10 micrometer range. This is performed by means of a linear actuator composed of stepper motor, nut and spindle. Due to the very restrictive requirements concerning resolution and backlash at temperatures in the 130 K range, the axial displacement is supported by flexible suspension elements.

The purpose of the Chopping Mechanism is to calibrate the thermal background emission of the FIRST telescope. This task can be performed with maximum efficiency by wobbling the subreflector about its vertex, in order to alternatively observe two pointing directions in the sky, symmetrical with regard to the mean direction of the main reflector thermal gradient. Fig. 2 shows an overall view of the location of FCM on the FIRST telescope as well as the detailed FCM configuration.

In order to provide applicability to applications other than FIRST, the functions of the FCM, namely refocusing and chopping, were clearly separated during the trade-off phase. In this way, the dedicated application of each separate function becomes possible.

This paper describes the technology development of the chopping function for which very challenging requirements were established.

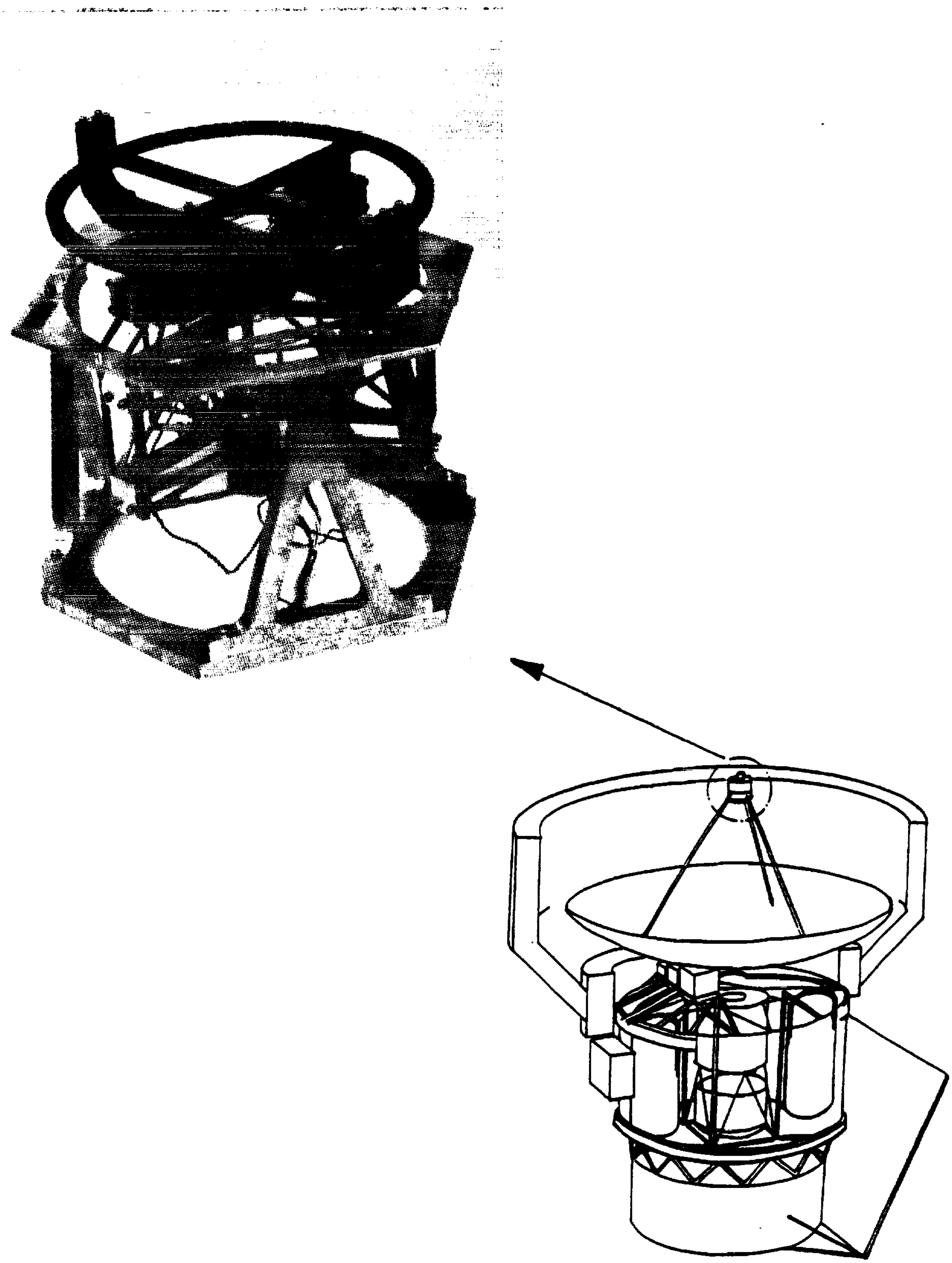

Fig. 2: FCM Configuration on FIRST Telescope

Requirements

The main requirements for the design of the Chopping Mechanism are

- a mechanism mass of 4 kg overall including the subreflector with a mass of 2.5 kg and
- an in-orbit lifetime of 3.6 years, which results in about 8 million chopping cycles.

The environmental conditions valid for the Chopping Mechanism are

- an operational temperature range of 130 to 150 K,
- additional ambient temperature for test purposes,
- vacuum conditions and
- quasi static launch loads assumed in the 20 g range.

The main performance requirements of the mechanism are

- a mass of 2.5 kg of the subreflector to be moved
- with a chopping angle of up to +/- 11.25 mrad,
- a chopping frequency between 0.01 and 5 Hz and
- an efficiency of 80%.

(Efficiency is defined as the relation between the time necessary to move the subreflector from one extreme position to the other and the complete chopping time based on the chopping frequency. This results in the requirement to move the subreflector in the maximum time of 20 msec from one extreme position to the other within a range of 3.75 mrad at a frequency of 5 Hz.)

An important performance requirement is the accuracy of the Chopping Mechanism, namely

- a position accuracy and reproducibility below 2%, that means e.g. 0.04 mrad at a chopping angle of 2 mrad,
- a tilt angle stability of 0.1% of the chopping angle, that means e.g. 0.002 mrad at a chopping angle of 2 mrad.

(Position accuracy describes the capability of the Chopping Mechanism to reach a specified position whereas tilt angle stability describes the capability of the Chopping Mechanism to hold a specified position.)

The defocusing of the vertex during the chopping motion must not exceed 10 microns and the decentering of the vertex is limited to 0.5 microns for an angle of 2 mrad.

Design Description

The Chopping Mechanism has to perform a lateral chopping motion of the subreflector about an axis vertical to the refocusing axis. This motion has to be performed reliable within the specified limits namely at a small chopping angle of maximum +/- 11.25 mrad with a very high position accuracy of better than 2%, a tilt angle stability of better than 0.1% and at high acceleration values required to move the subreflector within a minimum risetime. Additionally this performance data have to be achieved over a wide temperature range from ambient conditions down to 130 K.

Based on the set of performance requirements, a trade-off was established in the beginning of the study in order to determine the most suitable Chopping Mechanism design principle with the outcome to use magnetic actuators (moving magnet principle) attached to a fixed support yoke. The actuator induces the oscillating chopping motion of the movable subreflector support structure. The main advantages of this principle are its simple and reliable design, its very good dynamic behavior and its low interface complexity.

The design principle of the Chopping Mechanism is realized with two main elements - the structural yoke with the linear actuators attached and the subreflector support structure. Both elements are connected by the chopping rotational axis which is realized by a set of flexural pivots.

The structural yoke consists of a u-shaped support with two cross beams mounted rectangularly to the support by screws and set pins. The moving magnet linear actuators are fixed to the cross beams. The moving parts of the linear actuators are directly attached to the subreflector support structure. Additionally two non-contact inductive sensors are mounted to the cross beams. One sensor is used as position sensor for the control electronics, the other one for position monitoring during the motion.

The subreflector support structure is used in this design as a mounting base for the permanent magnets of the linear actuators, for the moving part of the position sensors and it allows to fix a dummy mass representative for the subreflector. Additional plates can be attached to verify different masses and moments of inertia for different subreflector configurations.

The design of the Chopping Mechanism is presented in detail in figures 3a and 3 b:

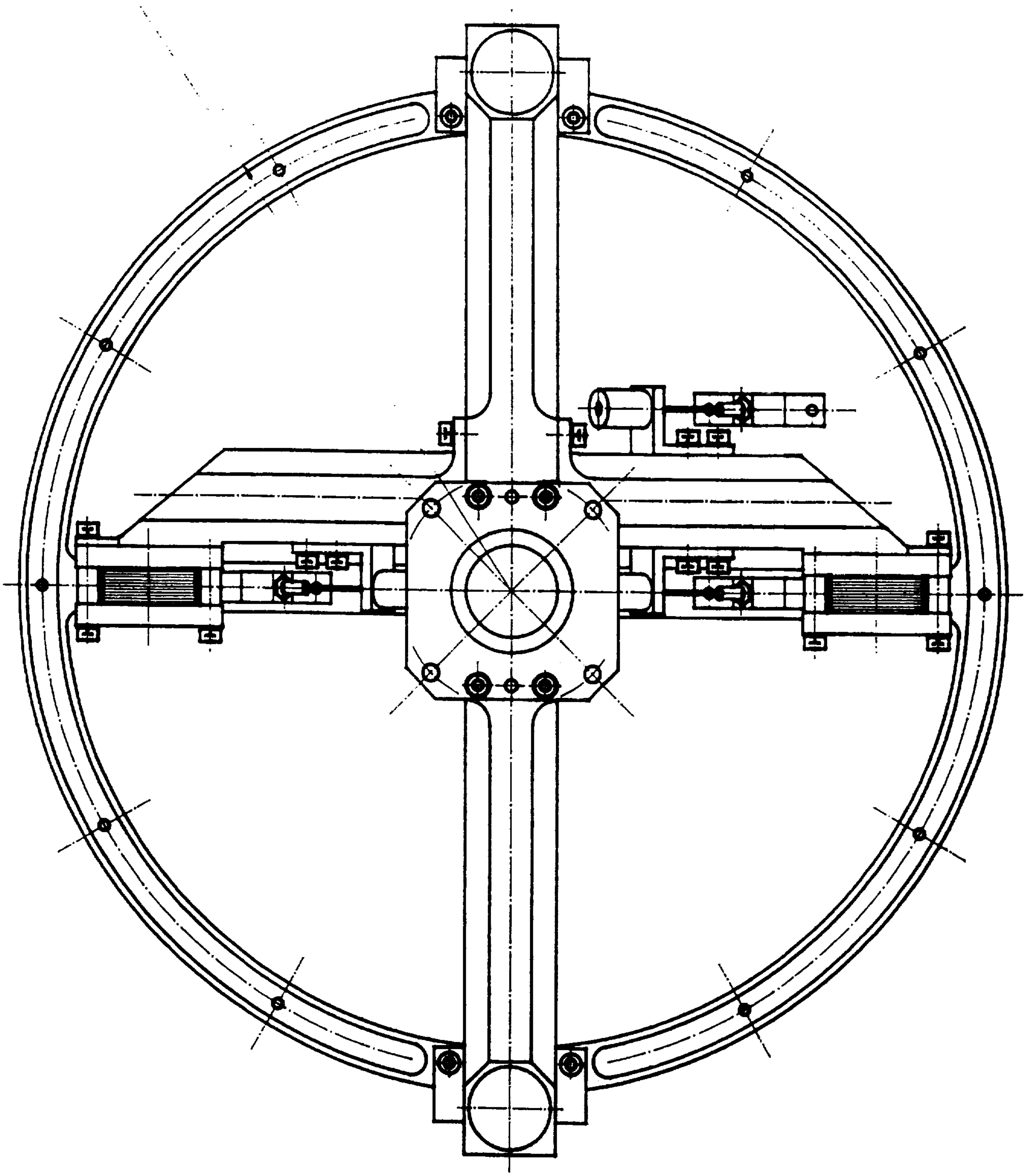

Fig. 3a: Design of the Chopping Mechanism - Top View

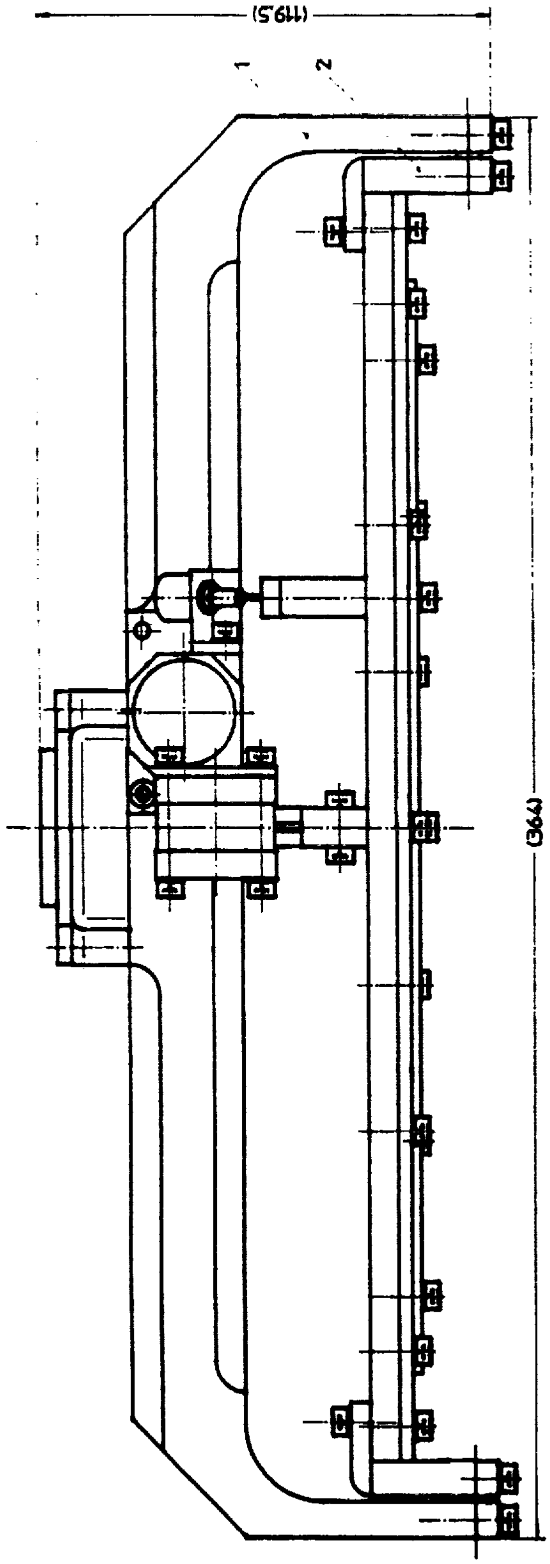

Fig. 3b: Design of the Chopping Mechanism - Side View

Linear Actuator

A magnetic linear actuator with moving magnet is used to perform the chopping motion of the mechanism according to the specified requirements.

In principle the linear actuator is composed of two symmetrical stator parts with a moving permanent magnet in the common air gap. The actuator force is induced by the interaction of the magnetic fields of the permanent magnet and the stator coil. The coils are powered in a way that the moving permanent magnet is pushed out of one stator part and at the same time pulled in the other stator part. The principle is independent from tilting of the permanent magnet in his plane as induced by the chopping motion of the FCM subreflector, that means there is no change of air gap between the magnet and the stator part during the chopping motion.

The principle of the linear actuator is presented in fig. 4.

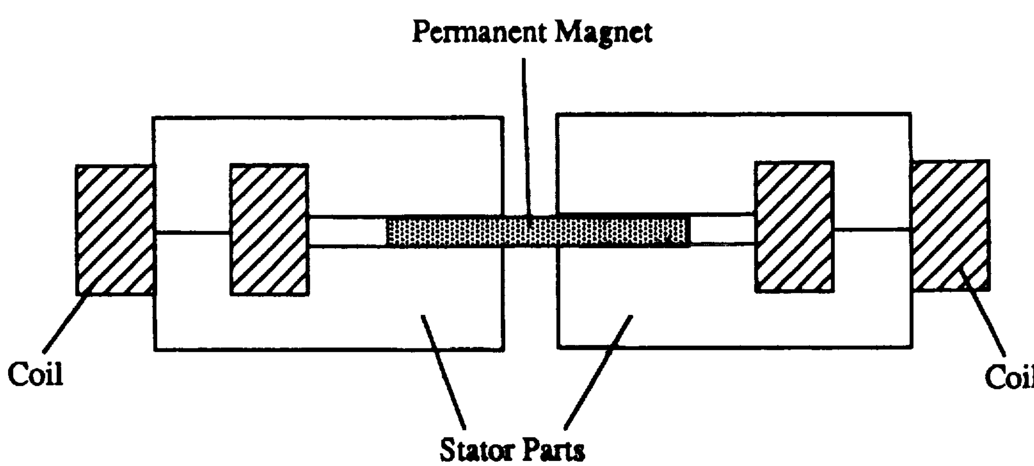

Fig. 4: Design Principle of Linear Actuator

The principle of the linear actuator described, allows for wide design variations which leads to simple and reliable solutions for the required chopping motion.

For the Chopping Mechanism discussed in this paper, the two stator parts were separated to obtain two independent actuators. These actuators was placed on both sides of the cross beam as shown in Fig. 3. This leads to a very simple design without additional levers required to transfer the output forces. Furthermore, due to the symmetrical arrangement, lateral forces acting on the flexural pivots during chopping motion are minimized.

The linear actuator was designed to achieve the requirements concerning chopping angle and acceleration. The required acceleration rate results in an actuator force of about 15 N (including margins).

The motion of the linear actuator is controlled by the control electronics. The interface between mechanism and electronics is formed by a contactless inductive sensor fixed on the cross beam. To obtain an optimal dynamic behavior of the Chopping Mechanism, three control loops with different tasks are inserted into one another.

The inner loop with the servo amplifier generates a current through the motor coils proportional to the control signal. It represents a fast integral-action controller (I-controller) with a time constant of 0.5 msec. The middle loop represents a velocity controller designed as proportional-action controller (P-controller). The outer loop represents the position controller designed as proportional-integral-action controller (PI-controller).

Tests Performed

To verify the functional requirements of the Chopping Mechanism, the following test steps were performed at ambient as well as at low temperature vacuum conditions with temperatures down to the 130 K range:

- Chopping Frequency
  Measurement of the subreflector response in relation to the commanded chopping frequency by means of a linear sensor

- Position Accuracy
  Measurement of the actual position of the subreflector in relation to the commanded chopping frequency by means of a linear sensor

- Angle Stability
  Measurement of the stability of a commanded subreflector position over a time period of up to 50 sec.

- Efficiency and Risetime
  Measurement of the time required to achieve a new commanded subreflector position

Test Results

- Chopping Frequency

The chopping frequency test was performed with different representative frequencies and at a maximum chopping angle of +/- 11.25 mrad. The frequencies chosen were the 0.1 Hz, representative of a slow chopping motion, the 1.4 Hz representing the mechanical rotational eigenfrequency of the moving mechanism and the 5 Hz representative of a fast chopping motion.

The Chopping Mechanism followed all required frequencies in ambient as well as low temperature conditions well.

- Position Accuracy

The position accuracy test was performed at different representative chopping angles namely the 0.25 mrad as representative of a very small chopping angle, the 2 mrad as representative of the nominal chopping angle and the 7.5 mrad as representative for a great chopping angle.

To verify the position reproducibility, each of the specified chopping angles was measured five times. The Chopping Mechanism fulfilled the required position accuracy at all angles well.

- Angle Stability

The angle stability test was performed by measuring the chopping angles 0.25 mrad, 2 mrad and 7.5 mrad over a time period of 50 sec at ambient as well as thermal conditions.

The output signal of the sensor during stability measurement was superimposed by the noise signal caused by the electrical test setup (0.017 mrad) which was higher than the required stability value.

- Efficiency and Risetime

The efficiency test was performed by measuring the risetime for a chopping angle of +/- 3.75 mrad at different chopping frequencies. The risetime represents the time passed for the change from the subreflector position -3.75 mrad to the subreflector position +3.75 mrad. To realize the required efficiency of 80%, this risetime has to be 20 msec for a chopping frequency of 5 Hz up to 100 msec for a chopping frequency of 1 Hz.

The test shows a dependency of the risetime on test temperature and vacuum conditions. For low temperature vacuum operation, the specified efficiency can be fulfilled for chopping frequencies of up to 1 Hz only whereas for ambient conditions an efficiency of 80% can be reached for chopping angles up to 2.3 Hz. This means that the specified requirement concerning the efficiency was not fulfilled with the actual design.

One reason for this result was given by the changed transient behavior of the linear actuator at low temperature vacuum conditions. The change in the transient behavior was found to be a reaction on eliminated air damping and of a change in the spring stiffness of the flexural pivots at low temperatures.

Another reason for not fulfilling the efficiency and risetime requirements is caused by the design of the linear actuator. The reasons for this fact will be considered next.

To summarize the functional testing, the following table shows the results of all tests performed:

Item	Predicted Values	Actual Values	+	-
Mass of Chopping Mechanism	< 1500 g	1418 g	x	
Mass of Subreflector	2500 g	2494 g	x	
Maximum chopping angle overall	22.5 mrad	22.8 mrad	x	
Chopping frequency	0...5 Hz	0...5 Hz	x	
Efficiency	> 80 %	80 % up to 2,3 Hz	x	x
Risetime for +/- 3.75 mrad	20 msec	43...90 msec		x
Position accuracy (< 1.875 mrad)	+/- 0.0375 mrad	+/- 0.011 mrad	x	
Position accuracy (> 1.875 mrad)	< +/- 2 %	+/- 0.03 mrad	x	
Angle stability	< 0.1 %	Noise Level		

Optimization of the Linear Actuator

As indicated in the previous section "Test Results", one main reason for the lack of performance concerning the efficiency specification is caused by the design of the linear actuator. Additional tests showed that the linear actuator generated a force in the 5 N range instead of the required 15 N. The tests also showed that this force is approximately dependent on the depth of insertion of the permanent magnet into the stator part.

This leads to the conclusion that the loss of actuator force was basically caused by the separation of the linear actuator in two different independent stator parts with two separate permanent magnets. By performing this separation the actual coil flux is reduced to only half of the expected theoretical coil flux. Thus the actual actuator force is also reduced to the half of the theoretical actuator force. Furthermore, saturation effects on the stator parts material caused an additional loss in actuator force.

To compensate for these problems, an upgraded new linear actuator with optimized design parameters was developed for inclusion into the Chopping Mechanism. The new actuator was manufactured with sheet iron cores instead of massive iron in order to reduce the saturation effects of the material and more windings on his coil were established to enlarge the actuator force.

The principal intent in choosing the separated actuator concept instead of the integrated one was to optimize the performance of the overall FCM system with the advantages of:

- Simple interface between the actuator magnets and subreflector moving parts
- Avoidance of lateral forces on the flexural pivots due to symmetric design
- Reduction of mass

The chosen concept which subdivides the integral actuator into two separate independent actuators however has the consequence that the electrical performance (actuator force) is reduced by the reasons described above.

Through the chosen measures and design changes, the actuator output forces were increased to a higher level compared to the original design. Thus an improvement of the overall chopping concept resulted.

The functional test results performed at ambient conditions for the improved design are listed as follows:

	Actuator Force	**Risetime for +/- 3.75 mrad**	**Efficiency of 80 % up to**
Original Design	5 N	43 msec	2.3 Hz
Improved Design	12 N	30 msec	3.5 Hz

Conclusions

The chosen design of the Chopping Mechanism provides an optimal solution from the mechanical point of view especially concerning:

- Symmetry of the design

- Only moments (no shear loads) are transferred via the flexural pivots (important for vertex shift during chopping motion)

- Simple actuator interfaces due to direct connection of the moving magnet to the movable structure of the Chopping Mechanism become possible.

- Low mass due to simple actuator concept

- Low thermal distortions at high temperature changes (low temperature conditions)

The chosen solution was found to be not optimal concerning the output actuator forces which would have been higher for an integrated actuator solution (double iron stator with one common magnet).

By introducing the improvements described above, the output force values and thus the performance values, particularly risetime, could be significantly increased. In this way, an optimal combination of the design advantages of the chosen concept together with improved actuator performance could be achieved.